Interference of microwave excitations of the conversion of electromagnetic and acoustic waves in W

T. M. Irklienko, A. P. Korolyuk, and V. I. Khizhnyĭ
Institute of Radiophysics and Electronics, Academy of Sciences of the Ukrainian SSR

(Submitted 22 June 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 3, 114–116 (10 August 1987)

An oscillatory effect associated with an interference of the wave-excitation and trajectory-excitation components of the deformation wave conversion mechanism has been observed at frequencies in the range 400–800 MHz at magnetic fields $\omega \sim \Omega$.

In metals with a long carrier mean free path l and at high frequencies, where the condition $l \gg \delta$ holds (δ is the depth of the anomalous skin layer), the deformation force of the interaction of carriers with the lattice is nonlocal. In weak magnetic fields, $qR > 1$ ($\mathbf{q}$ is the sound wave vector, and R is the radius of the Larmor orbit), it exceeds

140 0021-3640/87/150140-04$01.00

the induction force.[1] The deformation force formally includes two forces, differing in physical nature; one of them stems exclusively from the transport of momentum by carriers.[2] Under certain conditions the nonlocal nature of the deformation mechanism can lead to some interesting features in the wave-conversion effect. A theory for some events which are similar in physical nature and which occur in the absence of a magnetic field is reviewed briefly in Ref. 3 and also, for the case $\omega \ll \Omega$, in Ref. 4.

In this letter we report a study of the nonlocal wave conversion which occurs in weak magnetic fields under the inequalities given above and also $q \sim \delta^{-1}$, $l \sim d$, and $L \ll d$, where d is the thickness of the sample, and L is the sound attenuation length. The experiments were carried out by a hybrid version of the "passage" method.[5] A tungsten plate $d \sim 1.95$–2 mm thick was cut from a single crystal with a resistivity ratio $\rho_{300^\circ}/\rho_{4.2^\circ} = 4 \times 10^4$ by electron discharge machining. The experiments were carried out in a geometry $\mathbf{q} \| \mathbf{H} \| [100]$ at frequencies up to 800 MHz, with continuous oscillations. The magnetic field was varied within 0–6 kOe. The low-temperature apparatus is described in Ref. 6. The leakage level was below the sensitivity of the measurement system, -140 dB/W. The power applied to the sample was less than 50 mW. Experiments were carried out over the temperature interval 4.2–1.5 K. For the spectral analysis, the experimental data file was entered into the memory of a computer, and the spectral power was determined at the given frequency by means of fast Fourier transforms. To separate the conversion mechanisms, we measured the signal dependence $U(H), dU/dH$, with $\mathbf{E}(0) \| \mathbf{e}$, where $\mathbf{e}$ is the polarization vector of the transverse piezoelectric transducer, and $\mathbf{E}(0)$ is the vector of the electric field at the surface. At $qR > 1$ the conversion of this component occurs by a deformation mechanism.[5] In the course of single experiment we measured the electromagnetic excitation of sound and

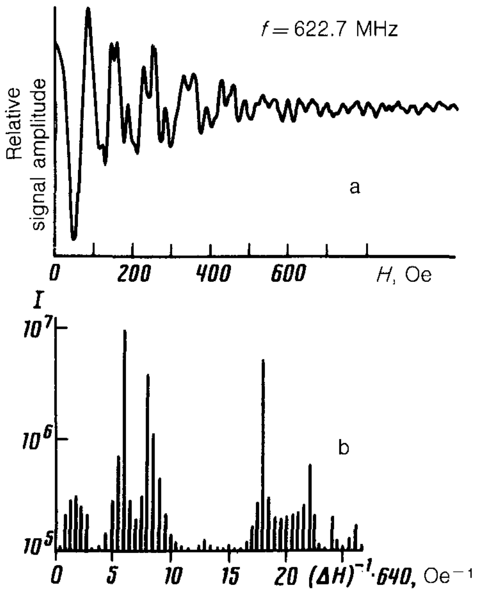

FIG. 1. a—Variable component of the signal representing the field dependence of the wave conversion efficiency; b—power spectrum of the conversion for the experimental curve in part a.

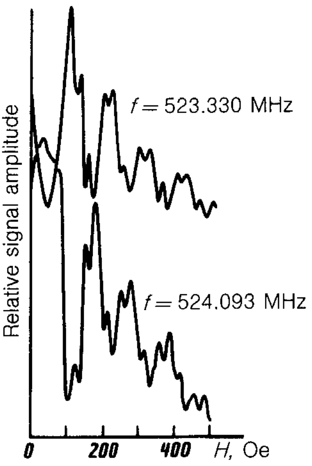

FIG. 2. Frequency inversion of the field dependence of the conversion efficiency.

the acoustic detection of the electromagnetic wave. We obtained the following experimental results.

1) A well-defined oscillatory structure is superimposed on the smooth $U(H)$ curve, which falls off monotonically with increasing magnetics field. The variable component of the structure is shown in Fig. 1a. The monotonic component had been observed previously in W (Ref. 5; the inset in Fig. 3) and also at frequencies 10–20 MHz in Ga, in Ref. 7. The shape of the lines in a field is a superposition of several oscillatory harmonics. The weak harmonic components for the measurements of dU/dH in a regime of synchronous detection were observed up to fields of 4 kOe for $f = 413$ MHz, where the monotonic component decreased to the noise level. The signal amplitude increased as the temperature was lowered from 4.2 to 1.5 K and was detected at a level no worse than between -90 and -100 dB/W at 1.7 K.

2) The shape of the oscillatory structure depends strongly on the frequency. The frequency interval $\Delta f_1 \simeq 0.7$ MHz leads to an inversion of the lines, as shown in Fig. 2; the interval $\Delta f_2 \sim 1.48$ MHz restores the shape of the oscillations.

3) Figure 1b shows the spectral power of the process for $U(H)$. The spectra were studied at various frequencies, including those used in recording dU/dH. Various weighting windows were used in the numerical analysis of the data. It was found that the positions of the characteristic surges in the spectral power (the periods of the harmonics in the magnetic field) were independent of the frequency. According to Fig. 1b, the characteristic spectral components have a constant period in a forward magnetic field.

From these experimental results we can draw a conclusion: The absence of a reference signal indicates the existence of more than two harmonic components. The frequency inversion of the lines indicates a change in the phase of one of the harmonics: the "reference" harmonic. Since we have $\Delta f_2 \sim s/d$, where s is the transverse sound velocity ($s = 2.90 \times 10^5$ cm/s; Ref. 5), the "reference" harmonic has a phase velocity approximately equal to s. The phase velocity of the other harmonics satisfies the condition $v_i \gg s$, since their phase changes only slightly as the frequency is varied over the range 400–800 MHz, and it is a linear function of the field H. The assumption $U_1 > U_i$, i.e., the assumption that the amplitude of the reference harmonic exceeds that of the fast harmonics, explains the frequency inversion of the lines for the wave of both circular and linear polarization. The fast harmonics with a small period (36 Oe and 29 Oe; Fig. 1b) are apparently acoustic analogs of Gantmacher-Kaner microwaves,[8,9] with a wave vector $K = (\omega \pm \Omega)/\bar{v}$, where $\bar{v}$ is the average carrier drift velocity along H, and the detected signal is a Rayleigh interference of acoustic-electromagnetic modes with various phase velocities. The physical nature of the powerful oscillations with a period of 111 Oe is not clear, however. This period, which corresponds to $(1/2\pi)(\partial S/\partial k_H) = 0.52$ Å^{-1} [k_H is the projection of the carrier wave vector on to **H**, and $S(k_H)$ is the area of the intersection of the Fermi surface with the plane normal to **H**], can be linked with holes with the extremal pitch of helical trajectories on an "octahedron" localized in the region of cross section A. However, the decrease in the amplitude in the field of this cross section does not depend on the frequency, and it occurs far more rapidly than the "background" of the conversion efficiency falls off. It does not correspond to the H dependence of the amplitude for trajectories of this type.[8,9] Furthermore, the spectral analysis shows that each fast harmonic has its own frequency inversion interval Δf_i. The measurements reveal $(s/d - \Delta f_i)/(s/d) = 10^{-3}$–$10^{-4}$. According to this model, this behavior can be explained on the basis that a time-of-flight term, $\omega d/v_i$, contributes to the phase difference between the fast harmonics and the "reference" signal. We believe that further experiments on the line inversion will reveal the cyclotron mass and drift velocity of the group of carriers with the extremal $\partial S/\partial k_H$, in a single experiment, without adjustable parameters. There is accordingly substantial interest in further theoretical and experimental research on the nonlocal conversion of electromagnetic and acoustic waves.

We wish to thank V. L. Fal'ko for a useful discussion and S. V. Plyushcheva for furnishing the tungsten single crystals.

[1] A. N. Vasil'ev and Yu. P. Gaĭdukov, Usp. Fiz. Nauk **141**, 431 (1983) [Sov. Phys. Usp. **26**, 952 (1983)].
[2] V. B. Fiks, Zh. Eksp. Teor. Fiz. **75**, 137 (1978) [Sov. Phys. JETP **48**, 68 (1978)].
[3] M. I. Kaganov and V. B. Fiks, Usp. Fiz. Nauk **150**, 159 (1986) [Sov. Phys. Usp. **29**, 888 (1986)].
[4] D. É. Zherebchevskiĭ, Fiz. Nizk. Temp. **10**, 713 (1984) [Sov. J. Low Temp. Phys. **10**, 373 (1984)].
[5] A. V. Golik, A. P. Korolyuk, V. L. Fal'ko, and V. I. Khizhnyĭ, Zh. Eksp. Teor. Fiz. **86**, 616 (1984) [Sov. Phys. JETP **59**, 359 (1984)].
[6] A. V. Golik, A. P. Korolyuk, and V. I. Khizhnyĭ, Prib. Tekh. Eksp. No. 2, 213 (1987).
[7] N. K. Batra, R. L. Thomas, K. C. Lee, and A. M. de Graaf, Phys. Rev. B **8**, 5473 (1973).
[8] T. G. Phillips, G. A. Baraff, and P. H. Schmidt, Phys. Rev. B **5**, 1283 (1972).
[9] T. M. Hsu and G. L. Dunifer, Phys. Rev. B **28**, 821 (1983).

Translated by Dave Parsons